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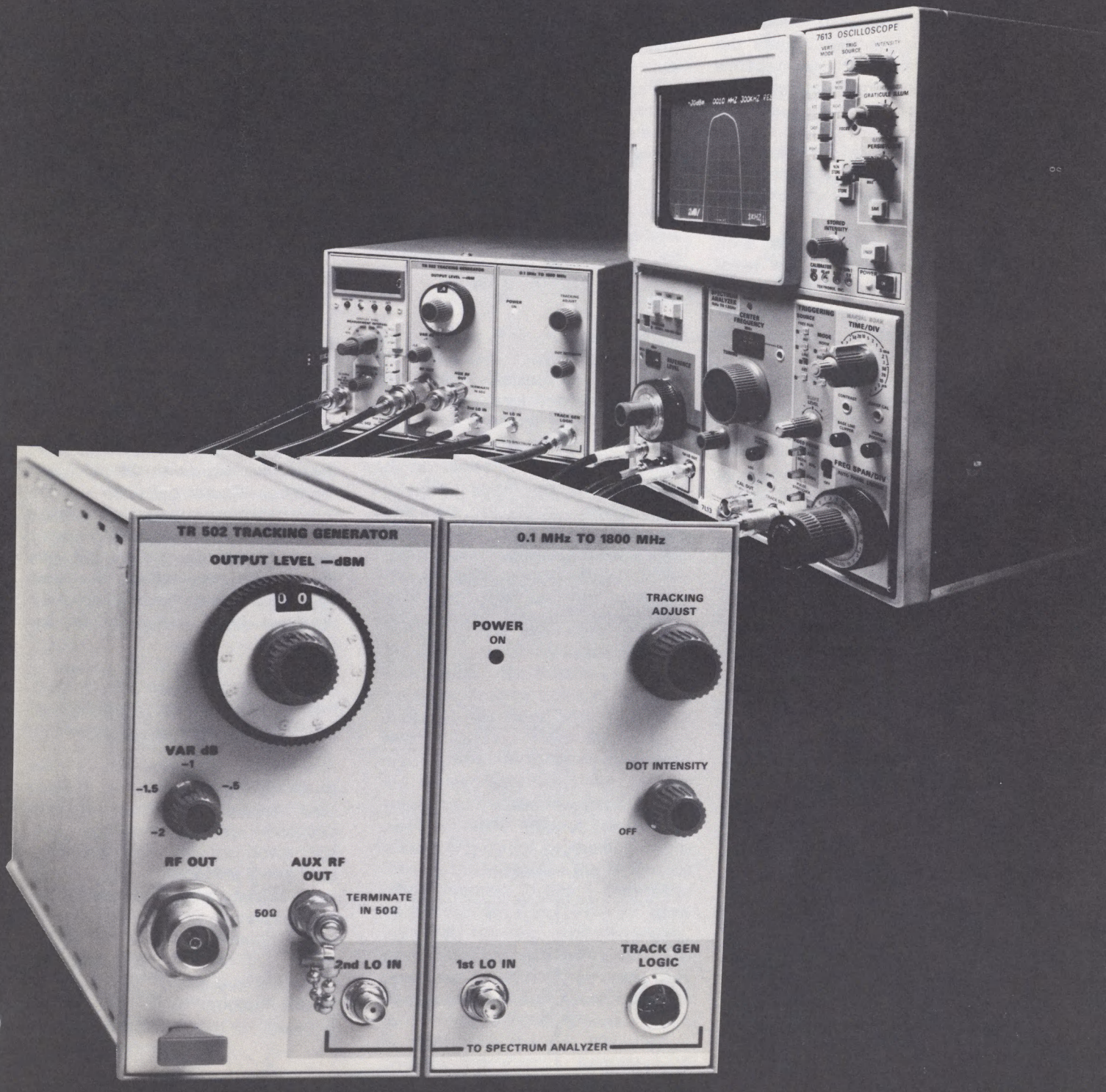
THE TRACKING GENERATOR/ SPECTRUM ANALYZER SYSTEM



THE TRACKING GENERATOR/SPECTRUM ANALYZER SYSTEM

By Morris Engelson

I. Introduction

A tracking generator (tg) is a signal source whose output frequency tracks in synchronism with the input frequency of a receiver, such as a spectrum analyzer (sa). Since the tracking generator's instantaneous output frequency matches the spectrum analyzer's instantaneous input frequency, the tg/sa system has the characteristics of a very sensitive synchronized detector. This leads to many novel as well as standard capabilities such as:

- frequency measurements with counter accuracy of low level (below −100 dBm) signals.
- accurate frequency measurement of the modulation components of complex signals.
- high dynamic range (over 100 dB) swept transmission characteristics measurement.
- return loss and swr measurement.
- usability as a stable cw signal source.
- a signal source with fm and other forms of modulation when used with accessory equipment.

This note describes how a tg/sa system works, and how to use such a system to make various measurements. Illustrations are based on the Tektronix TR 502/7L13 system. However, the operation and methods apply to any tracking generator/spectrum analyzer combination.

II. System Description

Frequency Tracking—Consider the basic block diagram of a typical tg/sa system (the TEKTRONIX TR502/7L13, shown in *figure 1).* The instantaneous spectrum analyzer input frequency (F_{in}) is related to the voltage tuned oscillator (vto) frequencies (F_1 and F_2) and the nominal if amplifier frequency of 105 MHz as follows:

$$F_{in} = F_1 - F_2 + 105_{if}$$

The instantaneous tracking generator output frequency (F_0) is given by:

$$F_0 = F_1 - F_2 + 105^{\varnothing}/_{f}$$

It follows that $F_{in} = F_0$ provided the spectrum analyzer's if amplifier frequency 105_{if} precisely equals the phase/frequency lock reference at 105 ∅/f of the tracking generator. The tg lock reference ($105\ ^{\varnothing}/_{f}$) is derived from a crystal oscillator. The if amplifier frequency (105_{if}) is derived from combining a 95 MHz crystal oscillator with 10 MHz crystal filters. Errors will be due to absolute accuracy of crystal oscillators, temperature drift of these oscillators, and center frequency accuracy and drift of the crystal filters. These are too many factors to control to the desired high degree of accuracy. Hence, there is a tracking adjust control which trims the output frequency so that F_0 equals F_{in}. This trimming is accomplished by tuning the tracking adjust control for maximum spectrum analyzer response at the narrowest resolution setting, with the tg output connected to the spectrum analyzer input.

Dynamic Range—Spectrum analyzer dynamic range is limited by the maximum input level for linear operations and the sensitivity. Sensitivity is still a limiting factor when operating a tg/sa system, but the upper input limit goes well beyond that set by the linear spectrum analyzer capability. Normally, overdriving a spectrum analyzer into the nonlinear region will produce harmonics and other spurious responses. However, due to the sweeping nature of the spectrum analyzer, it can only show a frequency component if that component exists when the instrument is tuned to that frequency. **With the synchronized tg/sa system, the input signal is always at the spectrum analyzer input frequency so that**

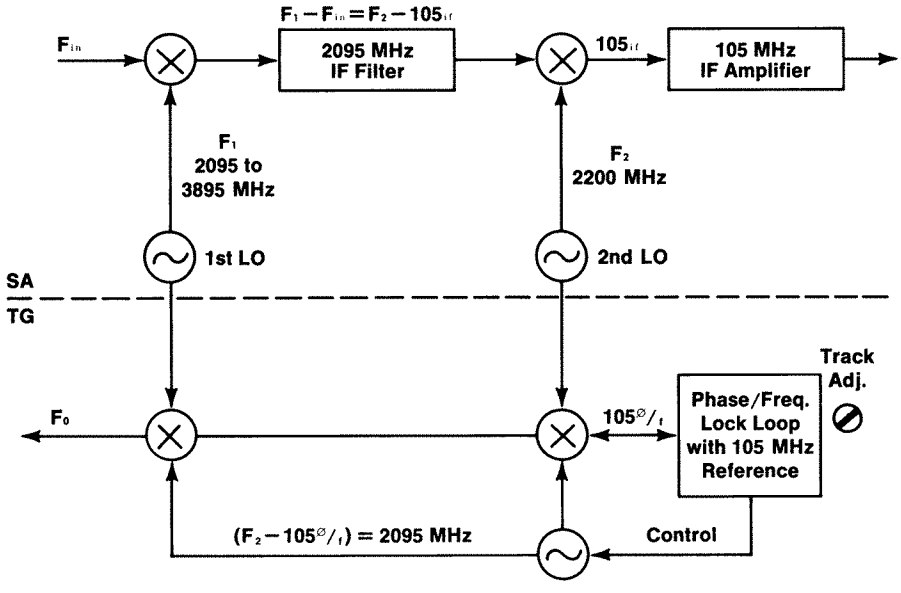


Figure 1. Simplified Basic Spectrum Analyzer/Tracking Generator System.

harmonics of that signal are not displayed. Hence, even though harmonics and other spurious responses may be generated, they do not show on screen to clutter up the display. Consequently the synchronous detection tg/sa combination has a very large dynamic range. The dynamic range of the TR 502/7L13 is 110 dB. This is 40 dB better than that of the 7L13 alone.

III. Frequency Measurements

The necessary equipment consists of a spectrum analyzer, tracking generator, and frequency counter. The illustration, *figure 2,* shows a 7L13, TR 502, and DC 502 Opt. 7 frequency counter. The signal whose frequency is to be measured is displayed on the spectrum analyzer. (Reasons for not connecting the signal directly to the frequency counter include too low a signal level or complex modulation characteristics.) The spectrum analyzer sweep is stopped momentarily at the center of the signal response. Since it is slaved to the spectrum analyzer, the tracking generator will, of course, automatically also stop sweeping at the same frequency. **Counting the frequency of the tracking generator output is equivalent to counting the input signal.**

Before proceeding with a measurement, it is necessary for the user to choose a resolution bandwidth setting. The narrower the resolution bandwidth setting, the better the theoretical accuracy due to reduced setting error. However, narrow resolution bandwidth settings may be difficult to handle because of spectrum analyzer drift. In fact, it is possible to obtain comparable results over a wide range of resolution bandwidth settings as shown in the following examples.

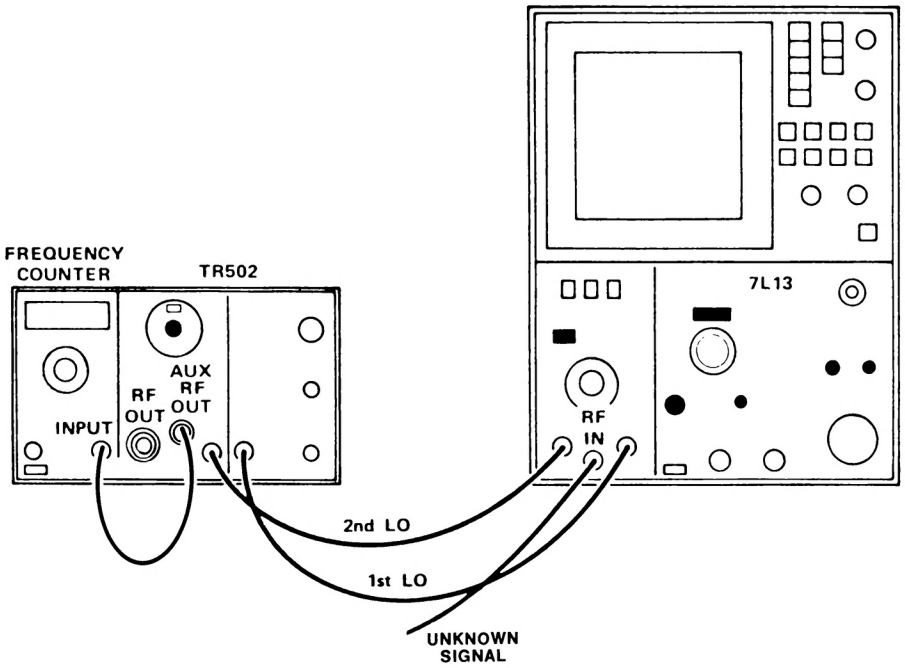


Figure 2. Frequency Measurement Equipment Setup.

There are three ways of stopping the spectrum analyzer frequency. These are: going to zero span, using manual scan, or using the "dot marker" feature of the tg/sa system.

The "dot marker" method is probably the most convenient method, but it is not routinely available on all instruments. This scheme requires a counter whose control logic is properly interfaced with the spectrum analyzer and tracking generator. Here the tg/sa stops sweeping momentarily while the counter determines the frequency. The additional dwell time of the beam at a fixed crt position produces a bright dot which represents the frequency being counted. *Figure 3* shows the spectrum analyzer display of a nominally 195 MHz, −84 dBm signal, using the dot marker mode. The spectrum analyzer frequency has been tuned so that the dot marker is centered on the response trace. At this point the DC 502, Opt 7 counter indicated a frequency of 194.4000 MHz.

Manual Scan, as the name implies, consists of manually scanning across the frequency span of the spectrum analyzer. The operator stops at the center of the displayed response. The advantage of this method is that any counter, rather than one specially designed to work with the tg/sa system, can be used. This measurement yielded a signal frequency of 194.4002 MHz.

The zero span method requires centering the signal response on screen

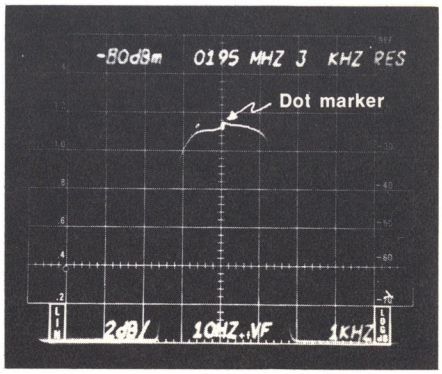


Figure 3. Sa display of signal whose frequency is to be measured. Note "dot marker" spot at center screen.

and then stopping the sweep by going to the zero span position. The trace now forms a horizontal straight line positioned at the peak of signal response. Fine spectrum analyzer tuning can be rocked to assure that the trace is at the peak of the response. *Figure 4* shows such a display. The frequency was measured as 194.4002 MHz.

The above measurements were done at a fairly wide resolution bandwidth of 3 kHz. This reduces accuracy somewhat, but makes for a fast, easy measurement by eliminating noticeable drift. A measurement at a 30 Hz resolution bandwidth setting yielded a frequency of 194.40026 MHz. Actual signal frequency as measured on the counter, after increasing signal level by removing attenuation, is 194.40023 MHz. Thus, the 3 kHz resolution setting yielded a discrepancy of up to 200 Hz, and the measurement using 30 Hz resolution bandwidth was in error by 30 Hz. These numbers are typical of what can be expected.

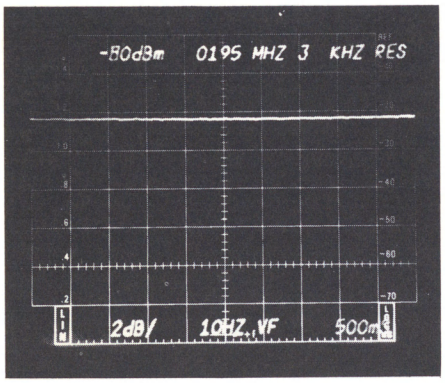


Figure 4. Signal display in "zero span" position.

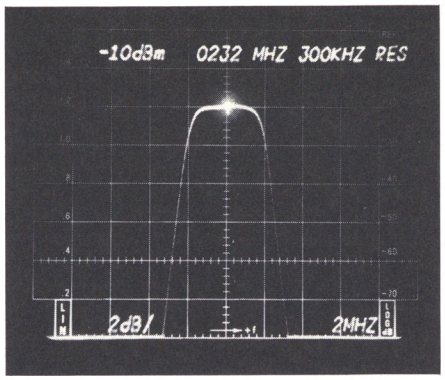


Figure 5. Bandpass filter transfer characteristic. Dot marker set to measure filter center frequency.

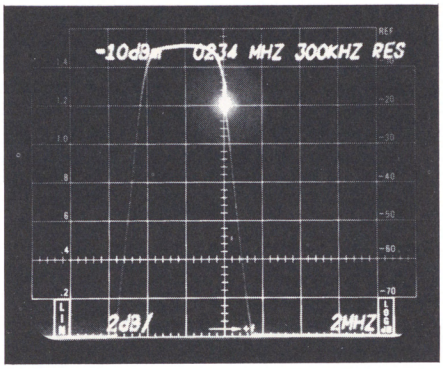


Figure 6. Bandpass filter. Measuring upper 3 dB frequency.

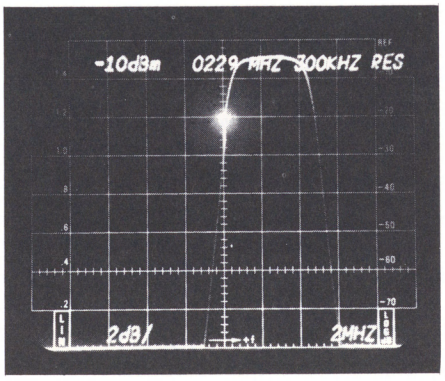


Figure 7. Bandpass filter. Measuring lower 3 dB frequency.

IV. Measuring Passband Characteristics

The tg/sa system is ideally suited to the determination of passband characteristics. The device under test, whose passband is to be observed, is connected between the tracking generator output and the spectrum analyzer input. **The amplitude of the constant level swept output from the tracking generator is modified by the loss or gain characteristics of the device under test, and displayed on the spectrum analyzer crt.** Accurate frequency and bandpass data is obtained by measuring the tracking generator output frequency with a counter using either manual scan or the dot marker mode of operation. The following photographs illustrate a typical measurement.

Figure 5 shows the passband characteristics of a tunable bandpass filter. According to the spectrum analyzer readout, center frequency is 232 MHz. Actual frequency as measured with a counter at the "dot" position is 231.7763 MHz.

Figures 6 and *7* show an accurate bandwidth determination. Here the tracking generator output was increased by 3 dB. Thus, the 3 dB down point is at the same display level as the peak of *figure 5.* This eliminates errors due to display nonlinearity when determining the 3 dB down point. At 2 MHz/div frequency span, the 3 dB bandwidth appears to be about 4.5 MHz. The actual 3 dB down frequencies as measured by the counter are 229.2730 MHz and 233.8826 MHz, yielding a bandwidth of 4.6096 MHz.

A useful filter measurement is that of stop band attenuation. This is illustrated by *figure 8.* Here, the spectrum analyzer is operated in the 10 dB/div vertical mode for maximum display dynamic range. The peak of the filter response is driven off-screen by 30 dB so that the stop band feedthrough is clearly visible. The stop band attenuation of the filter, when tuned to 281 MHz, is 90 dB. Stop band attenuation measurement to a level of 110 dB can be made using this system. Furthermore, the frequency of any part of the stop band can be accurately determined.

Bandpass gain or loss is also easily determined using the calibrated tracking generator output signal and the calibrated spectrum analyzer reference level. *Figure 9* shows the gain characteristics of a 100 MHz amplifier. This is a double exposure photograph. The flat horizontal line is the TR 502 output at −30 dBm. The upper, wiggly trace is the amplifier output showing a gain of about 30 dB. Bandpass ripple is a poor ±5 dB. *Figure 10* shows that this amplifier has quite poor bandpass characteristics. Substantial gain exists up to a frequency of 450 MHz. It is not flat, and has a great deal of ripple throughout.

As an aside, the 5 MHz periodicity of the ripple *(see figure 9)* led to the discovery of a faulty interconnecting cable in the amplifier.

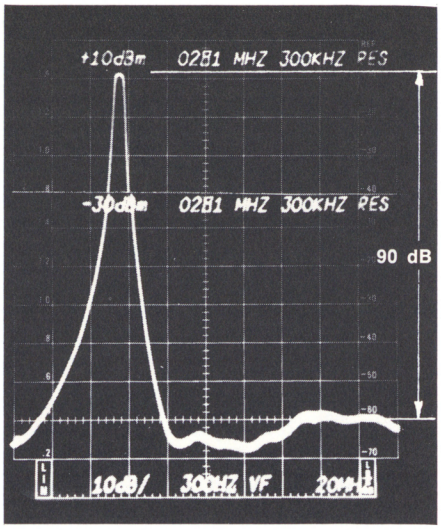


Figure 8. Composite photo. High dynamic range, filter stopband attenuation measurement.

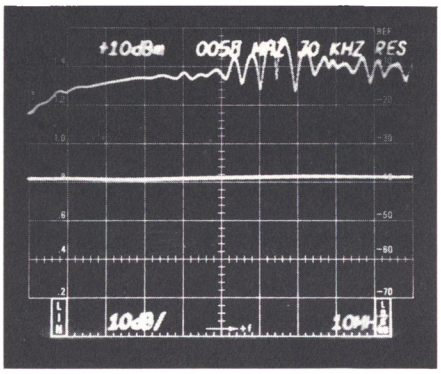


Figure 9. Amplifier passband gain and ripple display.

V. Return Loss and Swr Measurement

At rf frequencies it is the degree of impedance match rather than the absolute value of the impedance itself that is often of interest. Impedance match is characterized by various interrelated parameters. These are: characteristic impedance (Z_0), actual impedance (Z), reflection coefficient (ρ), return loss (rl), and standing-wave ratio (swr). These parameters are related as follows:

$$\rho = \frac{Z - Z_0}{Z + Z_0}; \quad |\rho| = \frac{SWR - 1}{SWR + 1}$$

$$SWR = \frac{1 + |\rho|}{1 - |\rho|}; \quad rl = -20 \log |\rho|$$

Thus, a reflection coefficent of $\rho = 1$ means a 0 dB return loss and an infinite swr. Conversely, an swr of one means a reflection coefficient of $\rho = 0$ with an infinite return loss. *Figure 11* is a graph based on the above relationships.

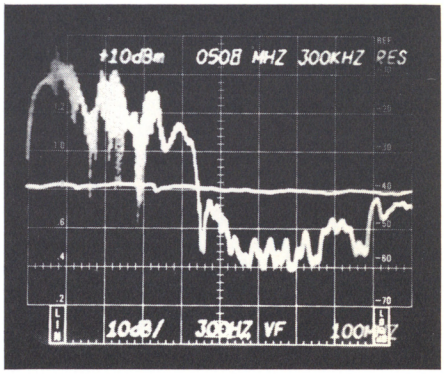


Figure 10. Amplifier passband gain stopband gain characteristics.

Figure 12 is a diagram of a typical test setup. A Wiltron Company type 60N50 SWR Bridge, which operates to 2 GHz, was used as the directional bridge. The device under test is a 432 MHz interdigital bandpass filter. *Figure 13* is a dual-trace photo showing both the transmission and return loss characteristics. Return loss at the center of the passband is 30 dB, corresponding to an swr of 1.065. Fine detail filter tuning can be displayed as shown in *figure 14.* This is a dual exposure expanded return loss display taken at a 7L13 vertical setting of 2 dB/div. The outer response is the same return loss curve as that shown in figure 13. The spectrum analyzer display cannot go below screen, hence, the clipped straight line on the bottom. The middle, wiggly line shows what happens when the filter is not properly terminated. Here the midband return loss has degraded to about 4 dB, an swr of 4.4 Clearly, output filter termination has a drastic effect on input impedance. With this system, output termination, coupling, and/or resonator tuning can be adjusted for best input return loss.

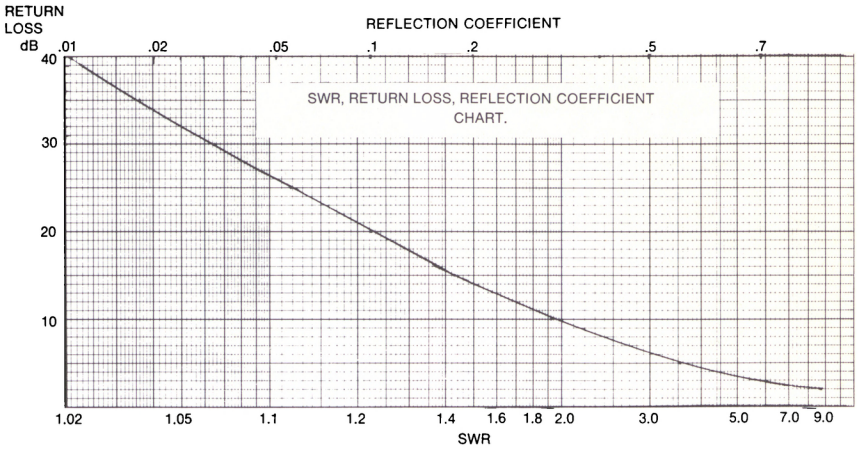


Figure 11. Swr, Return Loss, and Reflection Coefficient Chart.

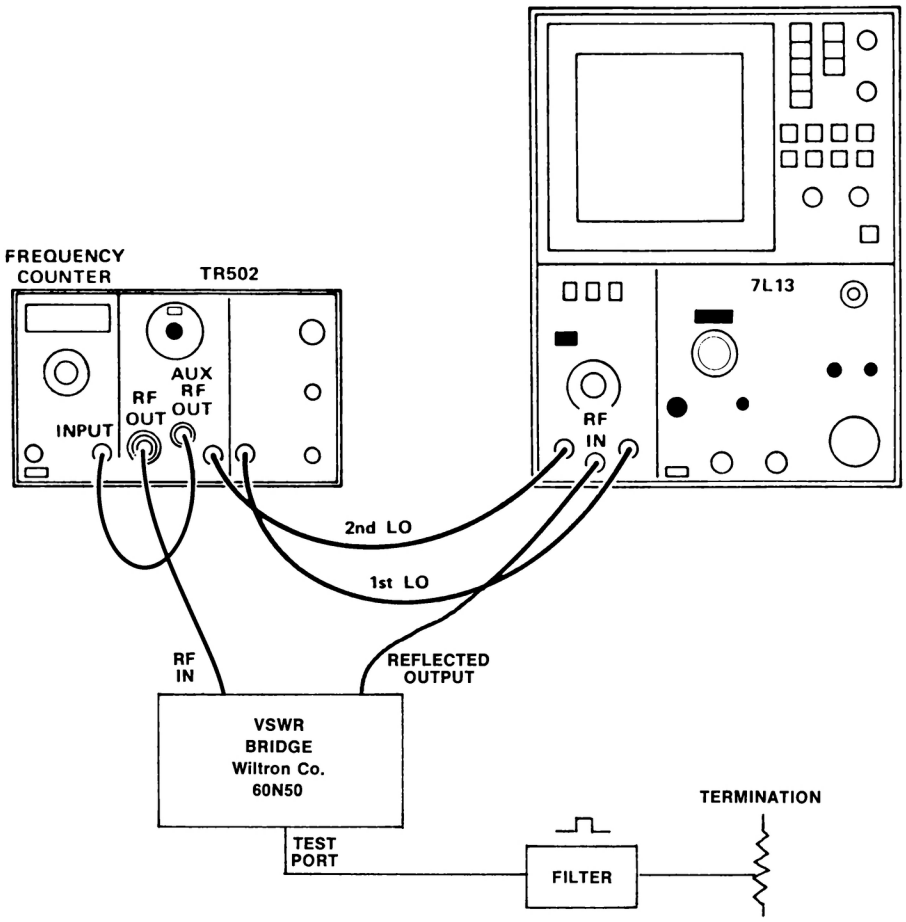


Figure 12. Reflection coefficient measurement equipment setup.

VI. Miscellaneous Uses

While this is not its prime function, the tg/sa system makes a highly stable general-purpose signal source or sweep generator.

The TR 502 in conjunction with a companion 7L13 can be used as a leveled sweep generator over the frequency range of 100 kHz to 1.8 GHz. Sweep width and frequency are controlled by the spectrum analyzer frequency span and center frequency controls. Unlike most sweepers, the output level is calibrated and can be controlled in 1 dB steps from 0 to −59 dBm. Also unusual, for a sweeper, is the system's high stability which permits sweep widths down to 200 Hz/div.

The high stability of the TR 502/7L13 permits the use of this system in lieu of a signal generator. The spectrum analyzer sweep is stopped by going to the manual scan, off, or the zero span position. This will produce a tuneable signal source with less than 10 Hz incidental fm when in a phase-locked position.

The tg/sa system is limited, as a signal source, by lack of wide range attenuation and modulation capability. To get a lower signal level than −59 dBm, it is necessary to use an external attenuator. Many types are available, including the Tektronix Type 2701, 0 to 79 dB in 1 dB step.

Let us now consider the matter of modulation. **Since the tracking generator frequency is controlled by the spectrum analyzer, it follows that fm can be generated by sweeping the spectrum analyzer.** The simplest procedure for the 7L13 is to set the sweep mode to external source. The degree of modulation is indicated by the length of baseline on the spectrum analyzer. Modulation sensitivity is controlled by frequency span setting and center frequency is controlled in the usual fashion. One precaution is to apply a dc offset to the modulating waveform in order to prevent clipping by centering the modulating waveform within the dynamic range of the horizontal amplifier. As the dc offset level changes, so will the horizontal position onscreen. Ideally, zero modulation should produce a baseline dot at center screen. A source of modulation, that produces the needed dc offset as well as various modulation waveforms, is the FG 501 Function Generator. With this signal source one can produce sinusoidal, triangular, sawtooth, etc, modulation functions over an extremely wide range of frequencies.

The modulation rate is limited by the response capability of the spectrum analyzer's local oscillators. The length of the generated baseline times the spectrum analyzer frequency span/div setting will give a fairly accurate indication of peak-to-peak deviation for modulation frequencies up to 100 Hz. The spectrum analyzer local oscillator drive circuits have amplitude roll-off for frequencies higher than 100 Hz. Under this condition, the width of the baseline will not give an accurate indication of deviation. Nevertheless, modulation rates in excess of 10 kHz are easily obtainable as demonstrated by *figures 15 through 18.*

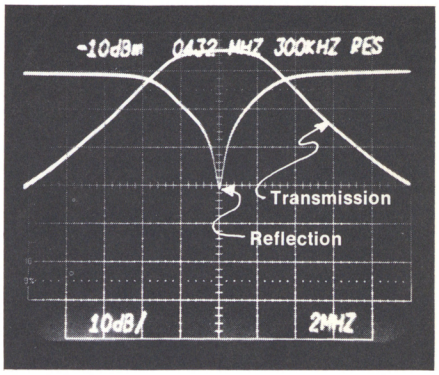


Figure 13. Interdigital filter, Passband response and return loss characteristics.

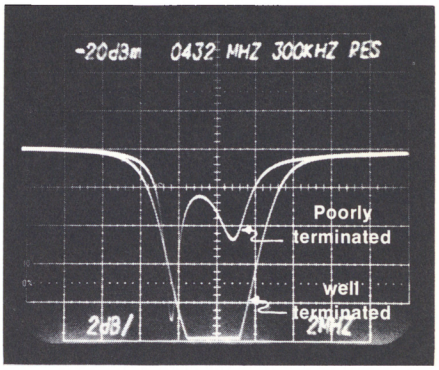


Figure 14. Expanded return loss characteristic showing the effect of termination mismatch.

Figure 15 shows the TR 502 output spectrum when the associated 7L13 was modulated by a FG 501 to the extent shown in *figure 16.* The output spectrum of *figure 15* was displayed on a separate 7L12 Spectrum Analyzer. This display indicates a fairly narrow deviation. *Figure 17* shows the TR 502 output spectrum at a modulation index of 2.4 showing a carrier null as predicted by fm theory. *Figure 18* shows the 7L13 baseline length at this setting. The 375 kHz 7L13 baseline length is much greater than the 56 kHz peak-to-peak actual deviation. Note, however, that the modulation is clean and symmetrical, with upper and lower sideband equal in amplitude. The generation of amplitude modulation is somewhat less convenient. This requires the use of an external mixer. Again, the FG 501 makes a fine modulation source, where the dc offset can be used for biasing the mixer.

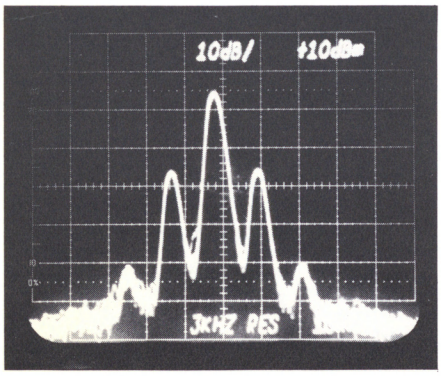


Figure 15. Narrowband fm spectrum generated by TR 502/7L13/FG 501.

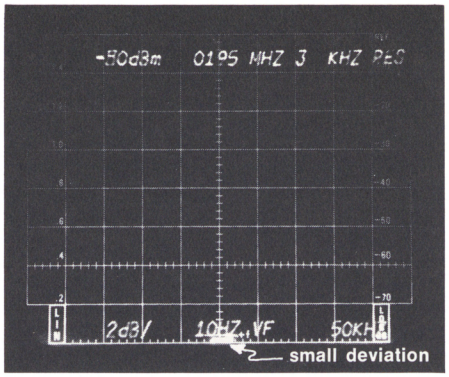


Figure 16. 7L13 trace display for spectrum of figure 15.

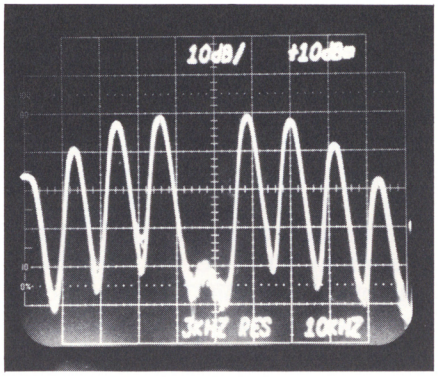


Figure 17. Wideband deviation for spectrum generated by TR 502/7L13/FG 501.

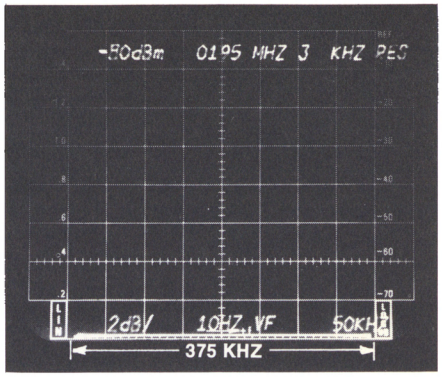


Figure 18. 7L13 trace display for spectrum of figure 17.

VII. Errors and Procedures

Tg/sa measurement errors can be separated according to frequency measurements and amplitude/dynamic range measurements.

Frequency—Two kinds of frequency measurements are possible. One type of frequency measurement involves the use of the tracking generator as a stimulus. The intent is to display and determine the pertinent frequencies of a network's transmission or reflection characteristics. Here the only measurement errors come from an inaccurate determination of the tracking generator output frequency. This error is quite negligible except when checking the characteristics of very narrow-band devices. A narrow-band device would be one whose bandwidth is less than the narrowest usable frequency span/div. For the TR502/7L13 this corresponds to a bandwidth of 200 Hz.

In the second case the intent is to determine the frequency of an incoming signal component which can not, for some reason, be directly measured. Here the tracking generator is used as a one-for-one frequency transfer device. We determine the frequency of the unknown signal by measuring that of the tracking generator. The accuracy of this technique depends on how well the tracking generator frequency corresponds to that of the unknown signal, and on how accurately the tracking generator output frequency can be determined.

The following list describes the sources of error when using the tracking generator as a transfer standard.

1. Tracking Adjustment Error: This error comes from inability to set the tracking generator frequency at the exact center of the spectrum analyzer resolution bandwidth response. *This inaccuracy is usually taken as one-third to one-tenth of the resolution bandwidth.*
2. Resolution Switching Error: This error is due to the fact that different resolution bandwidth filters may be tuned to slightly different center frequencies. The magnitude of this error depends on many factors, such as type of filter design, center frequency, bandwidth, etc. For the 7L13 this error can be up to 200 Hz. However, center frequency of the narrower bandwidth filters always fall within the passband of the wider bandwidth filters. *This error can, therefore, be minimized by adjusting tracking at the narrowest bandwidth of interest.*
3. Drift: Even the most stable spectrum analyzers will exhibit some degree of frequency drift. This is especially true for high accuracy measurements requiring a long counting interval. Some spectrum analyzers will exhibit up to a kilohertz of drift error. *This error is about 20 Hz for the 7L13.*
4. Signal Display Error: When determining the frequency of an incoming signal, it is necessary to stop the spectrum analyzer sweep at the center of the signal display. *This error is on the order of one-fifth to one-twentieth of the resolution bandwidth used.*
5. Incidental Fm: Short-term frequency jitter, known as incidental fm, will add to the uncertainty of what the tracking generator frequency really is. This is the major source of error in some tg/sa systems where incidental fm is several kilohertz. *The error for the TR502/7L13 is 10 Hz.*

Operating Procedure—For best results, adjust system tracking at the narrowest usable resolution bandwidth. This will minimize tracking error (1), and assure that the tg output is within the passband of all resolution bandwidth settings (2).

Whenever possible, operate the system in its phaselocked mode to reduce drift (3) and incidental fm (5).

Use a narrow, but not necessarily the narrowest, resolution bandwidth to display the signal whose frequency is to be determined (4). Use of a very narrow filter makes for a difficult and lengthy measurement due to system drift, but this gives the best accuracy. Use of a very wide filter eliminates problems of drift but increases signal display error. The best compromise is somewhere in between. For the TR502/7L13 system, the 300 Hz and 3 kHz resolution bandwidth positions are the compromise settings.

Amplitude/Dynamic Range—System dynamic range is the difference between the maximum and minimum signal levels that can be used. The following factors influence what can be achieved.

1. Maximum Drive Level: This corresponds to the maximum output level from the tracking generator. The drive level can be increased by use of an auxiliary amplifier. This technique should be adopted with caution because of the danger of damaging the device under test or the front end of the spectrum analyzer. *Maximum drive level available from the TR502 Tracking Generator is 0 dBm.*
2. Maximum Input Level: Active components, such as amplifiers, should not be driven to the point of compression. This requires an ability to reduce the drive level output from the tracking generator. The TR502 output level can be reduced to −61 dBm for such measurements.

   Passive components, such as filter, can handle power great enough to damage the spectrum analyzer front-end. The maximum safe input power level to the 7L13 mixer is +13 dBm. This can only be achieved by amplifying the 0 dBm output from the TR502. *One should always insert some front-end rf attenuation when operating with such potentially damaging power levels.*

A less obvious potential input level problem is that of spectrum analyzer compression. The 1 dB gain compression point for the 7L13, as for most spectrum analyzers, is at about −10 dBm input power. Here, the spectrum analyzer generates harmonics and other spurious responses. Of course, with the synchronized tg/sa system these are never displayed. However, the transmission band characteristics of the device under test will not show at the true level while the spectrum analyzer is under compression. Some spectrum analyzers have facilities for reducing if gain to the point where drive levels above the compression point can be displayed onscreen. The user needs to be careful not to fall into this trap when using such instruments. With the 7L13, all drive levels that may cause nonlinear operation go offscreen unless reduced by the front-end attenuator. *Consequently all onscreen displays are correct.*

3. The Noise Level: Spectrum analyzer noise level limits the minimum input amplitude that can be displayed. Noise level is a function of resolution bandwidth. *Thus, best sensitivity and dynamic range is achieved at the narrowest resolution bandwidth setting.* With −128 dBm sensitivity at a 7L13 resolution bandwidth setting of 30 Hz and maximum TR502 output of 0 dBm, the theoretical TR502/7L13 dynamic range is 128 dB. However, this cannot be achieved at all frequencies because of leakage.
4. Leakage: Leakage refers to a residual level of tracking generator signal getting into the companion spectrum analyzer even when the signal path between them is open. A variety of leakage paths are possible. *Tracking generator signals may get into the spectrum analyzer through the local oscillator connections* (see fig 1). This leakage is not affected by tg output level setting. *Leakage is also possible by radiation between the tg and sa cabinets, front panel fittings, and cables.* Here, the level of leakage may be affected by tg output level setting. It all depends on whether it happens before or after the output attenuator. In any event, baseline lift when the tracking generator is turned on is a sign of leakage. *For the TR502/7L13 system, leakage is at least 110 dB below drive level.*
5. Tracking Loss: Maximum display level occurs only when the tracking generator output frequency precisely matches the instantaneous spectrum analyzer input frequency. *Any mistracking between tg and sa means a loss of display level,* since the tg output is set on the skirt of the sa resolution bandwidth curve. Loss in display amplitude also means a loss in dynamic range.

Operating Procedure—For best results, adjust system tracking at the narrowest resolution bandwidth setting, even though a wider bandwidth might be used for the measurement. This will minimize tracking loss (5).

Reduce noise level by reducing resolution bandwidth (3). Keep in mind that reducing resolution bandwidth does not reduce leakage. It should also be noted that the narrower the resolution bandwidth used, the greater the likelihood of tracking loss. The 300 Hz and 3 kHz resolution bandwidths are the most likely to give best results.

Do not overdrive the input to amplifiers. Check for gain compression (2) by reducing tg output and observe that sa display follows. Reduce tg output if necessary. The TR502 output level goes down to −61 dBm.

Minimize system leakage (4) by using well-shielded cables. Broken braid or poorly grounded connectors are a major source of leakage. Leakage will show up as a baseline rise. Move cables or components around to find the best orientation for minimum leakage.

Specified minimum measurement dynamic range for the TR502/7L13 system is 110 dB.

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